UCRL-92512
PREPRINT

# CONCEPTS AND DEVELOPMENT OF DRIFT PUMPING FOR THE TANDEM MIRROR EXPERIMENT-UPGRADE (TMX-U)

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This paper was prepared for submittal to
11th Symposium on Fusion
Engineering Proceedings
Austin, Texas
November 18-22, 1985

November 11, 1985

## DISCLAIMER

CONCEPTS AND DEVELOPMENT OF DRIFT PUMPING FOR THE TANDEM MIRROR EXPERIMENT-UPGRADE (TMX-U)

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## Abstract

Low-energy ions trapped in the thermal barrier region of the TMX-U plasma cause a potential reduction which results in increased scattering and less thermal isolation between regions of the plasma. A method of removing these ions using magnetic field perturbations at the ion drift frequency has been developed. The concepts of "drift pumping" and hardware development are described in this paper.

"Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-ENG-48."

## Introduction

The Tandem Mirror Experiment (TMX-U) uses a low density magnetically-confined hydrogen isotope plasma for physics understanding of heating and confinement processes for fusion power. In the present system, microwave power is directed at specific regions to create populations of high energy electrons (ECRF). These regions are referred to as the Thermal Barriers and isolate electrons in the central region and plug regions from each other. The barrier regions must be kept free of low energy ions that tend to reduce the potential. The heating neutral beams aid in this process on the present system.

In a future experiment, a set of six tesla throttle coils will be installed in the transition areas between the central cell and plugs [1]. These structures will prevent the neutral beams from being used as particle pumps because of interference in the beam exit path. Other techniques for pumping these regions have been conceived and examined for feasibility. One technique that has received considerable scrutiny and was approved for fabrication uses a high frequency magnetic field perturbation to selectively enhance the diffusion rate of the undesired particles. The process has become known as drift pumping.

This paper includes an engineering theory for the process involved and discusses the system concepts for the hardware that has been assembled. In addition, two other papers are referenced and are a part of this overall activity [2,3].

## Theory

The undesired particles are confined to two regions by electrostatic and magnetic forces. The particles in the thermal barrier region will be removed by a high frequency magnetic perturbation intended to increase the diffusion rate of those specific particles. Figure 1 shows the regions that contain these low temperature particles.

The pumping process is simply described as a particle displacement caused by a displacement of the magnetic field along the x or y axis. If high temperature particles move rapidly enough through the perturbed field so that the net displacement will be zero. Certain low temperature particles with the proper bounce frequency match will traverse this region and when they mirror back thru the perturbed field it will have changed. This dramatically increases the radial diffusion rate fro the undesired particles. To produce the desired effects a magnetic field perturbation of 300 Gauss extending over a meter length is required. This field must also oscillate at a number of discrete frequencies in the 20 kHz range because the particle drift and bounce frequencies change as a function of temperature and position from the plasma axis.

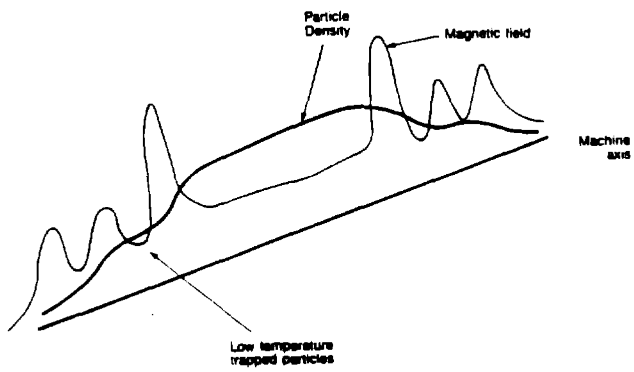


Figure 1.
Region of Trapped Particles

The maximum enhancement of the perturbation field occurs when the point of perturbation is near the region of maximum geodesic curvature. An angular displacement of the field at this region transforms to a large physical displacement where the confinement magnetic field has reached its maximum dimension. This displacement also places a limit on the maximum perturbation allowed; it should not drive the plasma into the magnet cases or other structures in the region. A plot of the magnetic field curvature is shown in Figure 2 where the position of the magnetic perturbation has been indicated.

In the following sections the system concepts are described and specific details are provided for the magnetic field perturbing coils.

## System Concepts

The physics requirements for the process included a minimum perturbing magnetic field over a meter length and a number of discrete frequencies in the 20 kHz range. Additional requirements included minimizing power requirements and providing a technique to increase the number of drive frequencies at a later period. The result of the examination of various approaches was a system that employs harmonic driving of a high-Q series resonant circuit. By pumping energy into the circuit, a large circulating current can be sustained to generate the required magnetic field using a set of coils in the experiment. The major components include the resonant circuit components, the perturbing coils, pulse driver, power conditioning and controls. Features of the resonator, perturbing coils and controls will be described in this paper. The two papers referenced include further details on the driver and system operation [2,3].

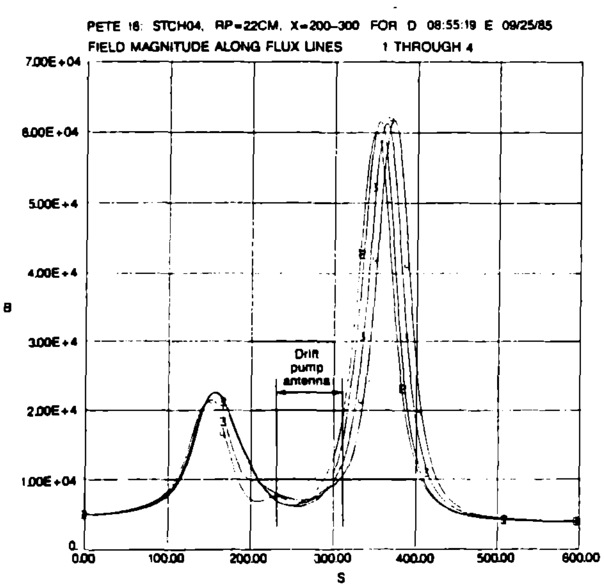


Figure 2.
Magnetic Field Valves Near the Drift Pump Antenna

## Resonator Description

Four separate antennas are incorporated into the vessel in the appropriate locations. Each antenna is part of the inductance of a resonant circuit in which large circulating currents are sustained. A schematic of the circuit is shown in Figure 3 and includes the element values.

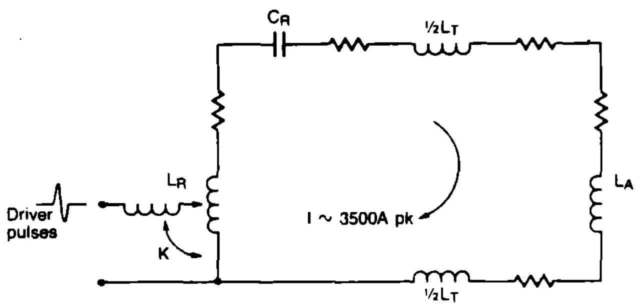


Figure 3.
Resonator Circuit

The design techniques for very low frequency circuits are classical, Terman's text [4] is a good reference for design considerations. We made use of specially designed capacitors and obtained a large Litz wire cable assembly for use in the inductor as well as a special Litz wire coaxial line used as the driver output feedline.

The inductor used has various tap points for exciting it and includes a rotatable single turn loop for fine tuning to the driver output. Only half the inductor is used presently, a later configuration will have an antenna coupled to two separate resonators tuned for different frequencies. A total of four exciting currents each with 3500A at separate frequencies will then be available.

The system Q is approximately 180 and at 3500A the system loss is about 2.5 J/cy. The driver will deliver a bipolar pulse with 10 J/pulse; this will allow pulse energy to be delivered to the circuit at a "sub-harmonic" $\frac{f_o}{3}, \frac{f}{5}, \frac{f}{7}$ frequency of the resonant frequency. The time between drive pulses provides additional recovery time for the SCR's in the drive unit.

The fabrication details of the resonator are important for the eddy current heating of the structures around the resonator coil can be large. The main housing is kept at least 12 inches from the coil in all directions yet after a few tens of pulses (75 ms long at 20 kHz), large areas of the aluminum cover were getting warm during our test. Numerous fittings closer to the coil were hot to the touch. No design changes were necessary however because the duty cycle of the test was far in excess of the normal duty cycle of the experiment.

## Perturbing Coils

The coils used to perturb the magnetic field confining the plasma are located in the two transition regions of the machine. The coil pairs together total a length of approximately 1 meter and when operated at 24 kA peak they should provide a 300-400 Gauss perturbation on the machine axis. Analysis of various structures using the McVey code [4] resulted in a slot antenna with multiple turns in the apertures. The mechanical design task for these antennae was formidable, the throttle coil assemblies were already fabricated and the antennae were forced to fit within the remaining space. The antennas are shown in Figure 4.

The circulating currents on the antennae will be large during operation and the resistive losses and forces on the adjacent conductors were a major concern. One-inch tubular copper is used as the conductor and all joints are made using copper braze. A support frame

| | Value | R | Q |
|---|---|---|---|
| Antenna | 3 μH | 3.8 mΩ | 100 |
| Capacitors | 6 μF | 1.3 | 10[3] |
| Inductor | 6 μH | 2.5 | 300 |
| Transmission line | 1 μH | 3 mΩ | — |
| | | 10.6 mΩ | |

Loss/cycle ~ 3.25J/cy at 20 kHz

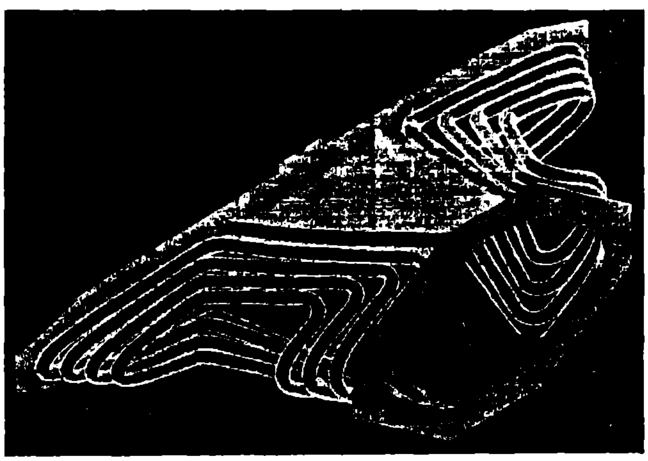

Figure 4.
Drift Pump Antenna

is used to keep the conductors separated during operation, the attractive forces between turns will approach (100-300) pounds for the 75 millisecond pulse during operation. The plasma will also tend to short out the conductors if its allowed to contact the region between the coil turns. Aperture-limiting plates are used on the ends of the coils as a means of limiting the plasma impingement as well as for the magnetic fringing field from returning around the end of the coils. An additional plate is mounted between the coils and allowed to float electrically to help grade the voltage gap between the adjacent ends of the two coil assemblies.

A test of the operation of the perturbing coils conducted outside of the vessel has been quite successful. We generated currents up to 4 kA peak using a single driver in a full system mock-up. The field generating characteristics are shown in the plots of Figure 5 where the components of field are shown against the estimated design field. A number of questions remain, however. The proximity of the coils to magnet structures inside the experiment vessel is anticipated to generate large eddy currents. These losses will be minimized by covering these structures with copper sheeting. We are also concerned about induced voltages in other loop-like structures in the experiment such as diagnostics components and getter wire systems. No specific solution has been proposed for these potential problems but simulation is planned to evaluate the magnitude of the problem.

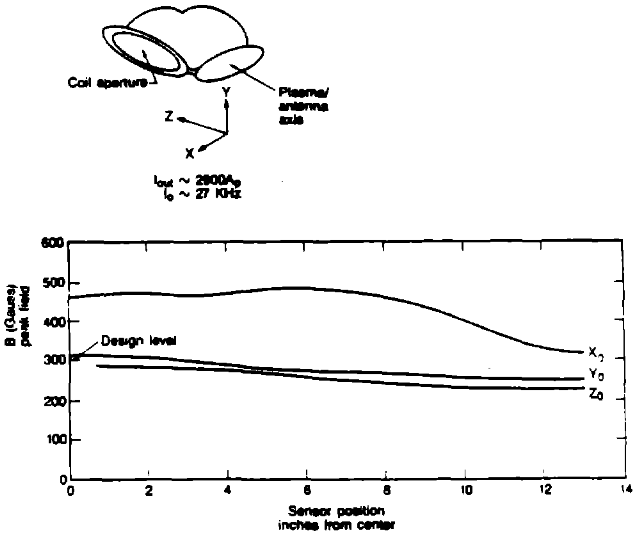


Figure 5.
Magnetic Field Generated by the Antenna

## Controls and Diagnostics

System control and monitoring is based on a desk-top computer and CAMAC hardware. This approach is common to the experiment so spare part requirements are minimized. A unique feature of this system however, is that it will acquire and preprocess physics diagnostics signals that are pertinent to its operation. A system block diagram is shown in Figure 6.

The controlling computer operates efficiently when coded using PASCAL and compiled. Its architecture is such that I/O operations are very rapid (>500 kwords/sec) and simply handled. The system computational speeds are not as fast as desired but commands, monitoring data acquisition and analysis of approximately 140 kwords can be performed between

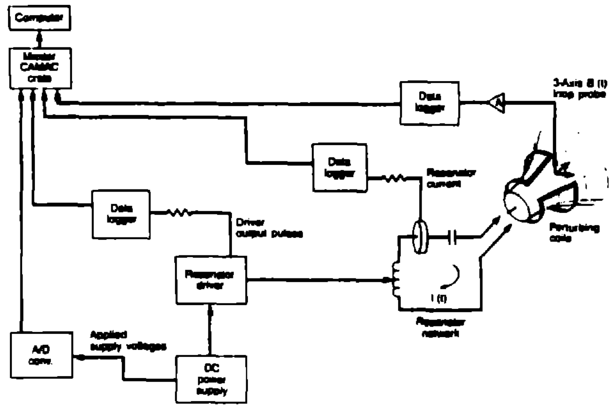

Figure 6.
Drift Pump System Diagram

operation cycles in 7-8 minutes. These tasks include the formation of a 16-bit control vector, 16 kwords in length. When stored in remote memory this forms the clocked sequence for 16 channels of binary on/off control. Data acquisition occurs after the plasma has subsided (75 ms plasma duration) at which point 64 channels of low speed recorders (5 kwords samples/sec) and 16 channels of high-speed data are transferred to the control computer.

Analysis includes envelope amplitude measurements, duration measurements, FFTs for frequency and phase, and magnetic field evaluations from 3-axis loop probes at the apertures of the exciting coils. After processing, the raw and filtered data will be available over a communications network and will be transferred to the main database for permanent archiving. Figure 7 is an illustration of the data and the data-handling system.

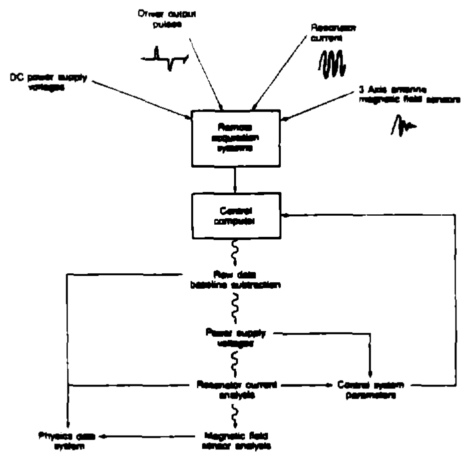

Figure 7.
Data Handling Concept

## Summary

This paper was intended as an introduction to the concept of Drift pumping and the initial hardware implementation on TMX-U. The theory in only conceptual, the hardware has been fabricated and tested externally.
Successful operation of the driver and resonator/antenna to specification levels has been verified. Further testing involving multi-frequency excitation and later development of high power Frequency Shift keying (FSk) operation are planned.

## Reference

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